PERGAMON Mathematical and Computer Modelling 0 (2004) 1–0
www.elsevier.com/locate/mcm

Performing Comprehensive Reception, Staging, Onward Movement, and Integration Analysis in a Theater of Operations

C. Van Groningen, D. Blachowicz, M. Braun and M. Widing
Argonne National Laboratory
Decision and Information Sciences Division
9700 S. Cass Ave., Building 900
Argonne, IL 60439, U.S.A.
vang@anl.gov <blach><duffy><widing>@dis.anl.gov

Abstract—The enhanced logistics support tool (ELIST) is a comprehensive information management and discrete event simulation program for analyzing the deployment of military units into a theater of operations. ELIST performs a detailed vehicle-level simulation of the reception, staging, onward movement, and integration of forces. This simulation receives loaded ships and planes at the ports, unloads them, and transports the personnel and cargo using air, water, rail, road, and pipeline modes of transportation. ELIST then generates a variety of reports and graphs that are structured to be multilevel, allowing the users to navigate through the results to determine the problems or constraints of the scenario. © 2004 Elsevier Science Ltd. All rights reserved.

Keywords—Military, Deployment, Simulation, Transportation, Java.

1. INTRODUCTION

Upon arrival in a theater of operations, military units must undergo extensive operations before they can be employed to perform their primary mission. Formerly, military planners had no tools for analyzing the complex deployment once the units and resupply arrived in theater. A deployment analysis tool called ELIST (enhanced logistics intratheater support tool) was created to fill this void. It uses a discrete event simulation to model a deployment plan in a constrained transportation infrastructure, identify problems with the plan, and test alternatives. The ELIST design is based on the experiences, observations, and requirements of many military logisticians, as well as military doctrine. ELIST provides facilities for analyzing questions such as:

- Can the seaports handle the required volume of ships and cargo?
- Does the road infrastructure need to be improved to handle the required amount of traffic?

This work was supported under a military interdepartmental purchase request from the U.S. Department of Defense, Military Traffic Management Command Transportation Engineering Agency (MTMCTEA), through the U.S. Department of Energy contract W-31-109-ENG-109.

- Are there enough transportation assets in the theater to move the supplies?
- Are military assets scheduled for the correct time periods?
- Are the transportation assets located where they can best be utilized?
- Are the personnel and equipment for the same units scheduled to arrive at the same time?

This paper describes intratheater deployment, discusses the scenario data used, details the simulation engine developed, summarizes the types of analysis performed, and concludes with some possible avenues for further work.

2. INTRATHEATER DEPLOYMENT

During a deployment, each military unit in the plan must travel from its home base to its destination in the foreign theater and be ready for its primary mission by a certain date. Supplies must also be delivered to the units at various times and locations.

Unit personnel, equipment, and supplies travel to the foreign theater on strategic assets. Once in the theater, equipment must be assembled and readied during staging. In a process called "marry-up," personnel and equipment that belong to associated units must join together at a specified location. En route to their in-theater destinations, units may perform additional activities at other locations as shown in Figure 1. All of these movements occur before the primary mission begins and are referred to as reception, staging, onward movement, and integration (RSO&I). ELIST models the intratheater deployment from the arrival of the loaded strategic assets through the completion of RSO&I.

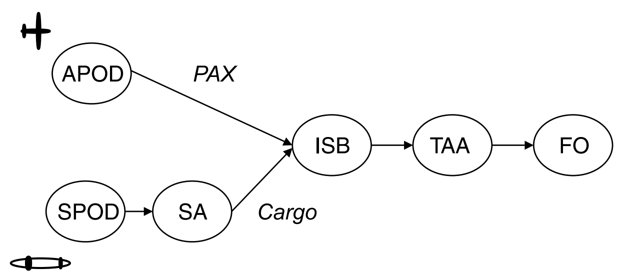

Figure 1. Typical unit deployment.

In a typical unit deployment, cargo and personnel arrive via plane at the airport of debarkation (APOD). The plane must land and park, and the people must disembark. The unit equipment arrives via ship at a seaport of debarkation (SPOD). The ship must be berthed, and its cargo off-loaded, documented, and moved to a storage area at the port. Often the unit equipment must then be moved to a staging area (SA) not far from the port where units are integrated. This integration may include unwrapping and reconfiguring cargo, marrying personnel with their equipment, filling units with their basic load of supplies and ammunition, and performing basic training.

In some cases, marry-up may be required at an in-theater staging base (ISB). ISBs are locations near the tactical assembly areas where units perform final training and integration before being employed as an integrated unit. A tactical assembly area (TAA) is usually considered the destination of a unit in the theater. This is the location where the unit begins its assigned mission. Some units also have one or more follow-on locations (FO). Follow-on locations are further destinations to which units must move as the plan progresses.

Within the theater, movement can be via road, rail, helicopter, fixed-wing aircraft, watercraft, or pipeline. Some movements require assets (e.g., military or commercial vehicles) to transport them to their final destination. Other movements occur with "organic" equipment, using the trucks or other vehicles belonging to the unit being moved.

The U.S. military maintains an extensive set of manuals documenting various components of RSO&I [1]. Processes, heuristics, and factors from many of these documents have been used in the development of the ELIST model. (See Section 7.) Other documents we used in developing our methodology include *Deployment Planning Guide, Transportation Assets Required for Deployment* [2], *Logistics Handbook for Strategic Mobility Planning* [3], and *Air Mobility Planning Factors* [4].

Other systems exist for analyzing and planning deployments. SUMMITS, scenario unrestricted mobility model for intra-theater simulation, evaluates the logistical feasibility of a proposed theater transportation course of action at a very detailed level. It does not model the full RSO&I, and it requires extensive setup. AMP, analysis of mobility platform, is a shell for integrating deployment systems that are modeling different pieces of a deployment. ELIST is one of the systems incorporated in AMP.

Most other work in deployment planning systems focuses on different parts of the whole deployment.

- JFAST: Joint flow and analysis system for transportation. JFAST is a strategic deployment tool used primarily for contingency planning. ELIST can use JFAST output directly for the initial unit movements into a theater. Additional information can be found at `www.jfast.org`.
- MIDAS: Model for inter-theater deployment by air and sea. MIDAS is a strategic deployment tool used primarily to analyze future force structures [5]. ELIST can also read MIDAS output directly.
- PORTSIM: Port simulation model. PORTSIM models the deployment of units through specified ports of embarkation (POEs) or ports of debarkation (PODs) at a detailed level. Additional information can be found at `www.dis.anl.gov/msv/PORTSIM.pdf`.
- TRANSCAP: Transportation capability model. TRANSCAP models the deployment of units from their power projection platform forts. Additional information can be found at `www.dis.anl.gov/msv/TRANSCAP.pdf`.

3. SIMULATION DATA

To analyze the feasibility and other aspects of an intratheater deployment, ELIST uses a discrete event simulation. All the data required by the simulation are grouped into an ELIST scenario [6]. A scenario includes the four major data sets as shown in Figure 2: network, requirements, vehicles, and movement rules. (A detailed description of these items can be found in [7].)

To represent the infrastructure of the theater of operation, the scenario uses a network of nodes, links, and features with associated data. The requirements include all the military units from

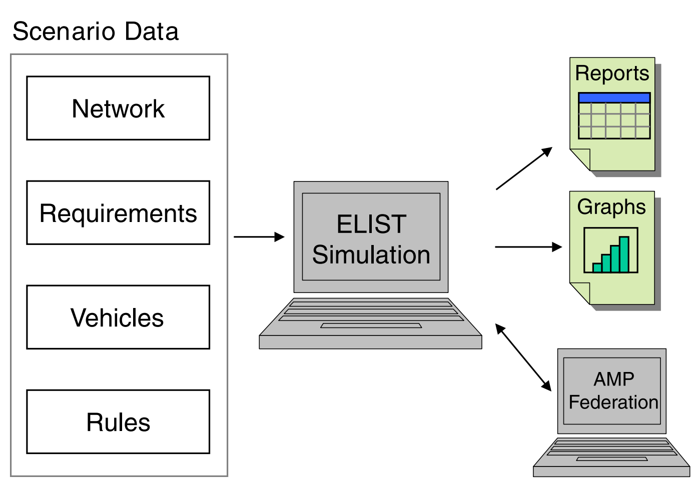

Figure 2. Scenario data.

the deployment plan with schedules of required tasks, locations, and times. Tasks include travel through the network, delays, and marry-up of related units. Vehicles available to the scenario must be specified so the cargo can be transported over the network. Finally, a set of movement rules specifies preferences about how each type of cargo can be moved.

These data sources are represented internally using objects in memory. A deterministic simulation is then performed using these objects. As the simulation runs, it translates the movement requirements into activities based on the preferences the user has made in the rules, as well as the current utilization of vehicles and network resources. Each activity is executed as a series of events. After performing the simulation, the user can view a wide range of reports and graphs that detail what occurred or send the results to presentation graphics programs for developing briefing materials.

In performing different types of studies, users focus on various parts of the analysis. Users can specify the level of model detail based on how the scenario is defined. Most significantly, users can select the level of detail at which to model the forces being deployed. The size of a plan can be considerable, involving tens of thousands of units with hundreds of thousands of people and millions of short tons of equipment and supplies. At times, the analyst wants to model the plan at a high level to get a quick idea of its feasibility, whereas at other times, a detailed analysis is required, such as to verify that all the heavy and oversized equipment can reach their destinations.

The following sections describe in more detail these components of an ELIST scenario which the user defines.

3.1. Network

The network contains nodes and links with attributes. Node types include airports, seaports, and intersections. Links are roads, railways, pipelines, or waterways. Air links are assumed to exist between any two airports and are not explicitly defined. Users can create networks built with external tools using data from military map products and other sources. They can import and tailor these networks to fit the scenario or define a network from scratch using the network editing functionality provided in ELIST. All of the locations referenced in the movement requirements must be represented in the network.

The quantity, availability, accuracy, and stability of data about the network are all vastly variable for different theaters. Decisions regarding the modeling of various capabilities of the infrastructure were based on how constraining that component would generally be to a deployment plan, and whether accurate data would usually be available. Berths, for example, are modeled on an individual basis at each seaport, with length, depth, apron width, and cranes. Most of a force arrives via ship, and if a ship cannot berth or be unloaded for some reason, that will have a large impact on the plan. On the other hand, resources that are somewhat subjective or imprecise, such as the capability of available personnel to load cargo on railcars, are modeled at a higher level, as a short-ton per day capability. Capability values that are not available or not critical can be set to a default value with little user effort.

Each node and link has a set of resources based on its class. Network resources are modeled in three ways within ELIST: as rate resources, gate resources, or capacity resources.

3.1.1. Rate resource

A rate resource is characterized by its ability to process a given amount of cargo or PAX in a given time. The personnel and equipment used to load containers on railcars are modeled as a rate resource. The capability of this consumable resource is expressed in containers per hour. The duration of an activity that requires a rate resource is at least the amount processed divided by the rate. However, the duration may be longer than the time dictated by one resource, in the case where multiple resources are required. The end time of an activity using rate resources is determined by

$$t_{\text{end}} = t_{\text{start}} + \max\left(\frac{A}{r_1}, \frac{A}{r_2}, \ldots, \frac{A}{r_i}\right),$$

where t_{end} is the end time, t_{start} is the start time, A is the total amount to be processed in the activity, and r_i is the processing rate of resource i required by the activity.

3.1.2. Gate resource

A gate resource also represents a capability described by a rate. However, no duration is associated with the use of this type of resource. Road capacities, for example, are modeled using gate resources; some number of vehicles may travel onto the road link each day. This rate, however, will not affect how long the trip takes to complete.

An activity requiring a gate or rate resource cannot start until a time at which *some* capability is available. Rate and gate resources model capabilities that are usually defined as some amount *per day* that can be moved, loaded, or otherwise processed. However, it is not necessarily true that this capability is evenly distributed over the day. To allow the analyst some flexibility in selecting how resource capabilities are distributed, a time interval smaller than 24 hours may be used to segment the capability. For instance, if an interval of six hours is selected, one-quarter of the daily capability is available during each six-hour interval. The smaller the interval, the more evenly distributed the capability becomes. This distribution does not affect overall capability of the resource or the duration of individual activities. It may, however, affect the start times of activities using a resource. Figure 3 shows a resource that processes 120 short tons per day using a 24 hour interval and a 12 hour interval.

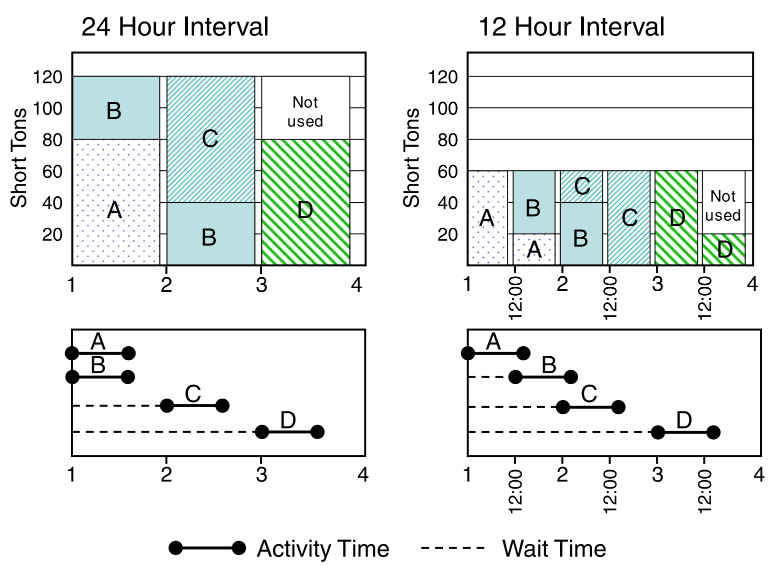

Figure 3. Resource availability and use for different intervals.

The resource is required for four events, each of which has 80 short tons of cargo, and each of which is scheduled for Time 1. The events all have the same duration, but Event B starts later when a smaller interval distributes the resource availability; it cannot begin until some resource capability is available for it. One might think that more intervals per day would extend the overall time of a scenario run as fewer activities requiring the same resource execute in parallel, and start time delays in these activities lead to further delays in subsequent activities. However, in ELIST scenarios where the numbers of activities and resources are large and their interactions are complex, no such trends have been observed.

Some infrastructure resources are modeled using variations of the rate, gate, or capacity resources. For instance, a four-rate resource is used to model crane capability. This means there is one resource, in this case the crane, that can perform four different types of operations at four different rates, specifically, on-loading bulk cargo, off-loading bulk cargo, on-loading containers, and off-loading containers.

3.1.3. Capacity resource

A capacity resource is a nonconsumable resource used for the duration of an activity. Its use has no impact on the activity duration. An example is a storage area at a port. A storage area is modeled as a resource with a capacity of some amount of square feet. An activity that requires storage area can commence when the required area is free. The required amount is held in use by the activity until it finishes; that portion of the capacity resource is then freed for another use.

3.2. Requirements

The requirements data contain the focus of an analysis: the deployment plan with all the units involved. A military unit includes personnel and their associated equipment and supplies. These cargo components, as well as attribute data and an ordered list of tasks for each unit, compose the requirements data. Figure 4 is a sample task schedule for a unit identified as 0ZHFC. The diagram shows its complete deployment, whereas ELIST usually models only the movements at the POD and beyond. This requirement shows that the unit must from through the origin (ORG) and port of embarkation (POE) before arriving at the port of debarkation (POD) with an earliest arrival date (EAD) of $C+20$ and latest arrival date (LAD) of $C+25$ (where $C+20$ refers to 20 days after the commencement of the deployment). The unit must then unload from the strategic asset and perform staging activities such as unpacking and reassembling equipment through day $C+26$. At the intermediate staging base (ISB), the linked rings indicate a marry-up requirement for the cargo and PAX as well as four days of integration activities such as acclimation, maintenance, and training. Finally, the unit must move to the destination (DST) by the required delivery date (RDD) of $C+35$.

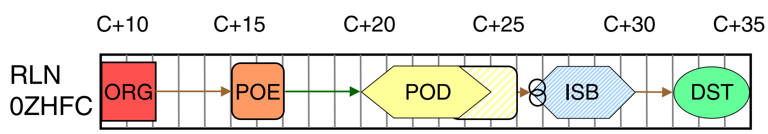

Figure 4. Sample unit schedule.

Each unit is composed of a number of cargo components. These components can be defined at multiple levels of detail. At the highest level, cargo components are defined by a commodity type and a number of people, short tons, or gallons. This level of component detail can be divided into multiple items with area specified as well. At the most detailed level, the components can be described as a set of items, each with a serial number, weight, and size dimensions. The analyst can select the level of detail to use for each unit in the simulation.

Movement requirements are usually generated by importing time-phased force deployment data (TPFDD) files. Unfortunately, the standard TPFDD format can only represent basic movement within a theater. To perform a substantive RSO&I analysis, a simulation needs more detailed information. To meet this need, Argonne developed a tool, ETEdit (expanded TPFDD editor) [8] for editing and augmenting a TPFDD to produce an expanded TPFDD (ETPFDD).

Three major modifications can be made to a TPFDD. In the standard TPFDD, unit cargo can only be specified in aggregate (up to Level 3) [9]. In the ETPFDD, however, more detailed items (Levels 4–6) can replace these aggregate quantities, providing a more accurate representation of the cargo, focusing on large, hard-to-move items, and stuffing containers with cargo. ELIST can model equipment and supplies as either aggregations of cargo with a specified weight and a generic weight-to-size ratio, or as discrete pieces of equipment with specified identifier, weight, and dimensions. Second, relationships between items can be modeled in the ETPFDD. This capability enables us to model associations between units for marry-up requirements. Built-in tools are provided in ETEdit to identify and associate groups of units as part of this modeling. Third, the ETPFDD allows additional movements to be specified for units, rather than limiting the unit to traveling to three locations in the theater. Often, marry-up, training, and other activities are required at intermediate locations, which are not represented in the standard TPFDD. An additional attribute that is added to each cargo component for the ELIST simulation is a commodity type.

3.2.1. Cargo categories

Five basic categories of cargo have been defined for ELIST and need to be moved in a military deployment:

- people (PAX);
- containers;
- breakbulk;
- roll on, roll off (RORO); and
- petroleum, oil, and lubricants (POL).

These categories are important to the simulation because they determine

(1) how the cargo should be handled during loading on and off vehicles,
(2) which attributes are important for fitting the cargo on vehicles (e.g., area, weight, volume), and
(3) how the cargo should be reported (e.g., weight, amount).

These categories are straightforward to assign to an amount of cargo. To accurately model how each piece should be transported, however, a "commodity type" must also be assigned to each item of cargo.

3.2.2. Commodity types

Each of the cargo categories is made up of one or more commodity types. Commodities allow the analyst to classify cargo into groups that have the same rules of movement. Before running a simulation, a commodity is assigned to each record of cargo by applying a set of commodity rules to the TPFDD data. Figure 5 shows some sample commodity rules with associated priorities and names.

Priority	Name	Rule
1	Water	if Cargo Category Code = "JDD" then Commodity = Water
2	Tanks	if Line Item Number = "T13305" then Commodity = Heavy Equipment Transport Required
3	Unit POL	if Cargo Category Cods = "POL" and Record Type = "U" then Commodity = POL Unit Cargo
4	Bulk RR	if Carco Category Code starts with "A3", "A7", "AD", "R7", or "RD" then Commodity = Bulk Tonnage RORO
5	Bulk BB	if Cargo Category Code position 1 = "3 ", "7", or "D" then Commodity = Bulk Tonnage Breakbulk
6	Outsized	if Cargo Category Code = "OUT" then Commodity = Outsized Tonnage
7	Oversized	if Cargo Category Code "OVR" then Commodity = Oversized Tonnage
8	Bulk	if Cargo Category Code = "BLK" then Commodity = Bulk Tonnage

Figure 5. Sample commodity rules.

The highest priority rule whose premise matches a record is fired for that record, and lower priority rules that may also match that record are ignored. This rule ordering allows each rule to be simpler, because fewer conditions are in the premise. The conditions are based on attributes in the TPFDD, such as record type, detail level, and CCC (cargo category code). For example, the first rule in the table assigns the commodity "water". These commodity rules and the commodity types that they create can vary from scenario to scenario depending on the focus of the analysis, the theater, and the types of transport available.

3.3. Vehicles and Assets

An ELIST scenario must include the vehicles available to move cargo and personnel within the theater. Numbers of vehicles are defined to work specific geographic areas, closely modeling the concept of operations utilized by the military. In addition, military transport unit equipment arriving in the theater can be made available to other units.

ELIST stores data on every vehicle type that might be used in a deployment. The model uses information such as payload, cargo area dimensions, curb weight, average speed, and average on-load and off-load times.

For a scenario, a specific collection of vehicles is defined. There are two ways to model vehicles in a scenario: "fully tracked" or "capability asset". A fully tracked vehicle is a discrete entity that makes loaded and empty trips and that always has a current location in the network, whether or not it is in use. A capability asset, on the other hand, is one or more vehicles that are considered to be generally available. Such a vehicle is only specifically modeled when it is being used to transport cargo. When its trip is finished, a vehicle designated as a capability asset returns to the pool, and it can be used immediately in an entirely different location. No empty vehicle trips are modeled for a capability asset.

Through the use of asset pools, analysts specify the geographic area where vehicles can be used. Asset pools are collections of vehicles that serve specific locations within the theater network. An asset can also be designated to serve all locations. Linehaul operations may be set up using asset pools of trailers that can serve a region and asset pools of tractors that can serve pairs of nodes. Asset pools have "home nodes" where all fully tracked vehicles congregate when they are idle.

Finally, the analyst may specify an interval of availability for each vehicle or group of vehicles. By default, an asset is available throughout the scenario. However, initial and/or final times of availability may be specified, if desired.

3.4. Movement Rules

Users must provide rules that specify how movement is to occur. Default sets of rules are provided with the system that can be modified to give the users flexibility to analyze new types of equipment and to focus on special areas of interest.

ELIST simulates five modes of travel: road, rail, air, water, and pipeline. For each of the first four modes, many different vehicles can be used. Some means is needed to specify both the possible and the preferred ways to move various commodity types within the theater. For example, it is possible to move personnel by buses, passenger railcars, and certain helicopters and aircraft. Movement rules are defined to represent these choices. Figure 6 shows a set of rules for transporting personnel.

The movement rules have a preference ordering for each commodity type with conditions based on its current time restriction and its distance to the destination. The time restriction indicates whether or not the unit can be late.

To simplify rule development and reduce the number of rules, the concept of an "asset type" is used. An asset type is a collection of similar vehicles that are used to transport the same type of cargo on the same mode, but with potentially different capacities or dimensions. For

Asset Name	Time Restriction	Distance Restriction	Miles
Buses	Any Time		
Helo	Any Time	<	25.0
Rail, Passengers	Any Time	>	115.0
C-130 PAX Only	Any Time		
ATT	Any Time		

Figure 6. Sample personnel movement rules.

example, one asset type used in Figure 6 is “C-130 PAX only”. This asset type includes several configurations of the aircraft such as C-130P, C-130EP, and C-130HP. Movement rules use assets to specify the vehicle selection. Using the rules shown in Figure 6, the second choice for moving personnel is by asset type “Helo” if the distance is less than 25 miles. These movement rules are used during the execution of the simulation described in Section 4.

4. SIMULATION

On the basis of the objects described in the data sets of the scenario, ELIST performs a discrete event-based simulation [10]. In the simulation, the requirements are translated into activities, and the corresponding objects are created. Activities are always scheduled at the earliest possible time. The simulation produces a delivery profile based on this push-forward methodology, and no attempt is made to detain or slow cargo that is arriving early (i.e., before its required arrival date).

Before simulation starts, each initial event will have a time at which to execute (its scheduled time) and be stored in the scheduled-events collection. During the simulation, each active event will either be scheduled at a future time, or will be waiting in one or more queues for currently busy resources or assets. Events waiting in the same queue or scheduled at the same time are executed in priority order.

Activities that involve unit components, such as trips to transport cargo, are assigned priorities based on the due dates of all units involved. Units with the same due date are prioritized in order of arrival or scheduling (i.e., FIFO). These priorities minimize the wait time of most units, while testing the scenario feasibility. Activities that do not involve units, such as return trips of unneeded trucks, are assigned lower priorities.

An activity that cannot successfully execute at its scheduled time because some condition is not met, or some resource or asset is not available, is put into one or more queues. The activity will wait in these queues, until it can acquire the needed resources. Queues are created by the simulation as they are needed—one queue for each constraining network resource, asset, or condition. The events in a queue are not attempted again, until that queue is triggered when its associated object becomes available.

At each simulation cycle, an event is selected and executed. The selection procedure is illustrated in Figure 7. Events are scheduled at Time t while the queues are always at the current time. The next item to be processed is the item with the highest priority (p).

Each active event has a priority, with a value of 1 being the highest priority. When the simulation is ready for an event, it first executes events in queues that have been triggered, marked in gray. The events in the second queue execute first, as it has the highest priority, having inherited the highest priority of its events. Events in that queue execute in order until the resource associated with the queue is no longer available. This method was chosen over selecting the highest priority event from all triggered queues after each event execution, for model runtime performance reasons.

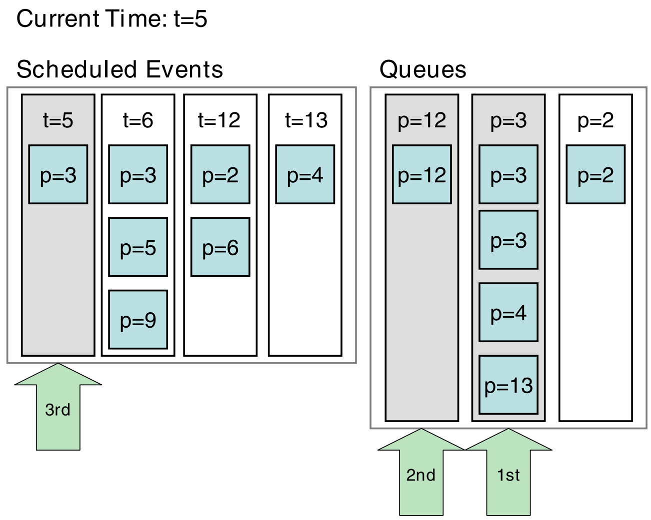

Figure 7. Event priority and execution order.

When no more queues are ready, the first event scheduled at the current time is executed. Before execution of each subsequent scheduled event, the queues are again examined. When there are no more triggered queues, and no more events scheduled at the current time, time is advanced to the time of the next scheduled event.

The simulation of the unit movements begins with their arrival in the theater on strategic ships and aircraft. These data may be generated by another military model, such as JFAST (joint flow and analysis system for transportation), or by a subprogram within ELIST. From these data, ELIST builds and schedules a set of initial events, which model the asset arrivals with their unit cargo. Units may alternately start as "available" at a location within the theater.

During a simulation, a cargo entity completes an activity when it is released by the final event of that activity. At that time, the cargo attempts to implement its next scheduled requirement. If the cargo entity has no more requirements, it is done and is added to the final delivery profile. Final delivery for a unit is achieved when *all* of its components have completed their last movement requirement.

4.1. Activities

Using the options specified for the scenario, the movement requirements in the ETPFDD are translated into the following requirements in the simulation:

- marry-up with one or more other units,
- implement a delay,
- begin operating as asset vehicles,
- begin operating as a resource, and
- move to a location.

Activities model all these tasks in the simulation. Many activities are composed of multiple subactivities, which must be scheduled and executed in order. Each activity checks for the resources and conditions required for successful completion; if all conditions cannot be met, the activity waits in the appropriate queues. If an event succeeds, the next subactivity is scheduled.

Of the five requirement types listed above, the first four are straightforward. No decisions or choices are involved; in fact, to implement a delay, operate as assets, or operate as a resource, no conditions are even required. Movement to a location, however, is much more complex. Fulfilling a move-to requirement can involve initializing a trip, assigning assets, loading vehicles, traveling on routes, and using convoys. The following sections examine some of these activities in more detail.

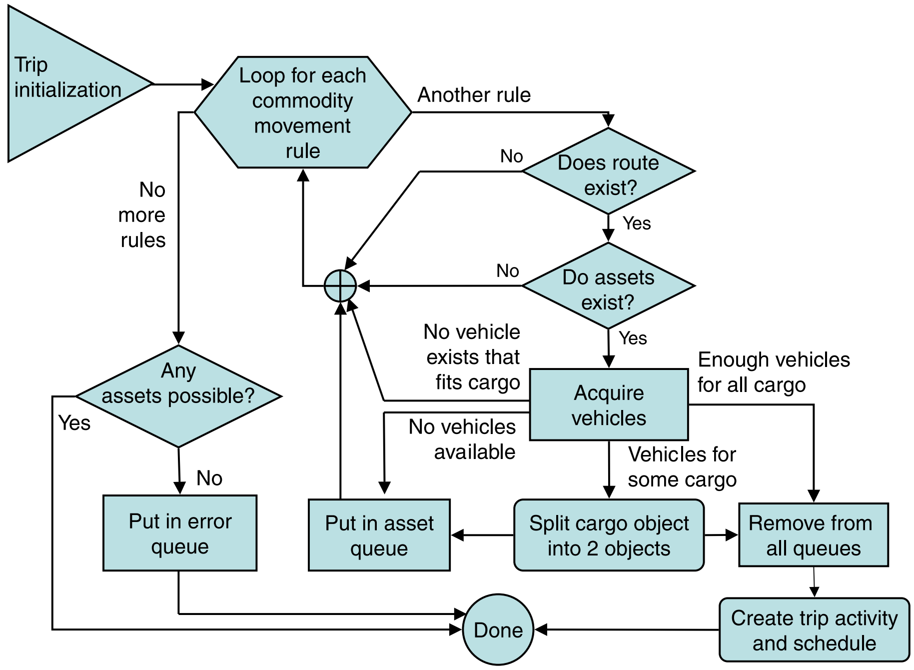

Figure 8. Trip initialization logic diagram.

4.1.1. Trip initialization

A trip initialization is created and scheduled to meet all move-to requirements. Some of these requirements specify the mode to be used, whereas, for others, the movement rules must be used to select both the mode and the asset type. A trip initialization consumes no time (except possibly queue time) as it examines the modes and vehicles possible. Figure 8 is a logic diagram of initializing a trip.

When a trip is initialized, the movement rules for the commodity to be moved are used in priority order. The event with the cargo goes into an error queue if the scenario does not include vehicles that can move the cargo or if an appropriate route does not exist to the destination. The event waits in asset queues if, at that time, no vehicles are available at the location of the cargo. If vehicles are available that can hold some of the cargo, the cargo object is split into two objects: one moves ahead on the vehicle, while the other remains in the trip initialization object, waiting in asset queues. When this activity is completed, it will have ensured that a route exists, selected assets, created a trip activity of the selected mode, and assigned the vehicles or asset capability and cargo to the trip.

4.1.2. Asset queues

A trip initialization activity is put into one or more asset queues if the cargo location does not have appropriate assets. At this time, if this type of asset is available elsewhere in the network, a new activity is created and scheduled to move these assets to the cargo location. These empty assets are not, however, specifically tagged for that cargo. Instead, they are matched with the highest priority event in the queue at the time that they arrive.

When a trip activity that utilizes assets completes its unload subactivity, the vehicles are released. When vehicles are released, and there is an associated asset queue with waiting events, the queue is queried as to whether additional assets might be required. The queue keeps track of the number of expected assets (i.e., the number that has been sent from other locations, but has not yet arrived). If more assets are required than expected, the newly free assets are sent as well.

4.1.3. Vehicle loading

Determining whether assets are available to transport a piece of cargo begins with determining whether a vehicle can accommodate the size or weight of the cargo. There are different constraints for loading each cargo category on various types of vehicles. Loading people and gallons of POL is straightforward because all vehicles have numeric quantities that specify the amount they can carry. Loading container cargo onto vehicles is also straightforward. Each vehicle has an attribute for the number of 20 foot containers that it can carry. In addition to the number of containers, the weight of the loaded containers must be less than the weight capability of the vehicle. Weight is a limiting factor for all vehicle types and all cargo categories, except people and POL. Some vehicle type/cargo category combinations also use area as a factor. In addition, the loading of airplanes requires that the cargo fit through the door.

Ideally, only full vehicles would depart for a destination. However, there is not always enough cargo traveling between two nodes to fill a vehicle. Another consideration is the time cargo may spend waiting for additional cargo to fill the vehicle; this wait should not be unlimited. ELIST deals with these factors by having parameters that allow the user to tailor loading to the conditions in the scenario. For each mode, two scenario parameters are used: adequate load and maximum wait. These parameters are used as follows. When an event with a new asset is first created, it is assigned a given amount of cargo. The percent load which that cargo constitutes is calculated by using either weight (for breakbulk and RORO) or amount (for containers, people, and gallons of POL). If the percent load is greater than the adequate load, and if no other cargo is waiting, the vehicle can depart immediately. Otherwise, the activity is put in a special queue where it stays for no more than the maximum wait time. Other appropriate cargo arriving within that time can be added to the waiting activity. Whenever an adequate load is reached, the vehicle can depart.

Air and water travel use an additional parameter—minimum load. This value is used when requesting assets from other locations or when determining if it is time to begin loading cargo on a ship or aircraft. It is necessary to have a minimum load of cargo before an empty ship or plane will be sent to a new location to pick up cargo. In this case, the time cargo waits is not limited, as ships and planes are not used to transport such a small amount of cargo. Instead, small amounts of cargo are usually transported via rail or road.

4.1.4. Routes

After a vehicle has been loaded, the simulation selects a route. ELIST finds routes for all movement requirements before the simulation is run. For each known origin and destination pair, a route of each mode is stored, if one exists. The user can modify the default route set by changing the search criteria from the default of shortest distance to the greatest capacity or shortest travel time. Different criteria can be selected for different paths. Multiple routes can be stored for the same nodes and modes with different priorities. Specific routes can also be assigned to specific purposes. For example, a route can be specified as being required for use by either commercial or military assets.

Nodes and links can have "limits" that constrain the size or weight of vehicles and cargo that can travel over them. A tunnel or bridge, for example, limits the height of the vehicle. Thus, not all cargo can travel over all routes.

When more than one route could be used for a vehicle, the highest priority route is tried first. If it is busy, the trip activity checks the next route. If all routes are busy at the time an activity is ready to depart, it waits in one queue for each route. When it departs, it uses the first available route.

As the ELIST simulation runs, it searches for a new route if it needs a route that it does not have stored and it has not yet tried to find. Because military practice recommends limiting the number of routes, the simulation will not search for another path just because the existing path is busy.

Although a route is composed of a set of links and nodes, the simulation treats it as one entity. When a route is needed, the available capacity of the entire route is checked. This ensures that a vehicle will arrive at its destination without unwanted en route delays, and prevents the simulation from having to schedule and execute multiple events for every route traversal. Intersection capacity must be available for each node, and entrance capacity must be available for each link at the time that the vehicles will reach that section of the route. Both links and vehicles have a speed attribute; a vehicle on a link travels at the slower speed. Using the speed and link length, the time of arrival at the end of each link is calculated. The capacities available at that time of the next node and link are then checked. In this way, the number of vehicles that can depart at a given time (interval) is determined. Any additional vehicles wait in a queue for that route which is triggered at the next time with route capacity available.

4.1.5. Convoys and trains

ELIST gives the option of grouping some types of ground vehicles in convoys. Convoys are created based on the following scenario parameters:

- minimum vehicles per convoy,
- maximum vehicles per convoy,
- maximum wait,
- rate of march, and
- spacing distance.

Activities with road vehicles wanting to make a trip that requires a convoy are put in a convoy queue. Such an activity waits up to the maximum wait time to form a group of at least the minimum vehicles per convoy. If this number is not reached within the wait time, a smaller convoy departs. A convoy never has more than the maximum vehicles per convoy.

Once a convoy departs, the next convoy does not depart until the first convoy has traveled a minimum of the spacing distance. The convoy travels at a speed given by the rate of march, unless a vehicle or link speed is slower. In that case, the slower speed is used for the applicable portion of the route.

Rail travel is always performed using trains (i.e., strings of railcars moving as a group). The movement of trains is controlled in the same way as convoys. Locomotives are not explicitly modeled in ELIST; it is assumed that they are always available.

4.2. Results

When an analyst has completed (or partially completed) a simulation, many reports and graphs become available. Generally, the first chart an analyst examines is the delivery or closure profile. This chart provides an overall view of the success of the deployment plan. The example shown in Figure 9 includes all breakbulk, RORO, and container cargo in the plan. Delivery can also be viewed by cargo category, commodity, or a user-defined set.

The lines in the graph show the total amount of short tons (of breakbulk, RORO, and containers) required at all PODs and all destinations in the plan. The areas are the amounts delivered to the PODs, the SAs, the ILOCs, and the TAAs. The frontmost area shows the short tons “closed”, i.e., those whose entire unit has arrived at its TAA (destination). The amounts not delivered can also be determined.

The availability and use of every network resource, every asset pool asset and vehicle type, and every route can be graphed. In addition, all resources, assets, and conditions that constrained movement during the simulation can be listed, and those amounts that are waiting can be graphed over time. Figure 10 shows a constraints report; constraints are listed in order of severity, measured by the number of intervals during which use was over 90% of capacity. The time at

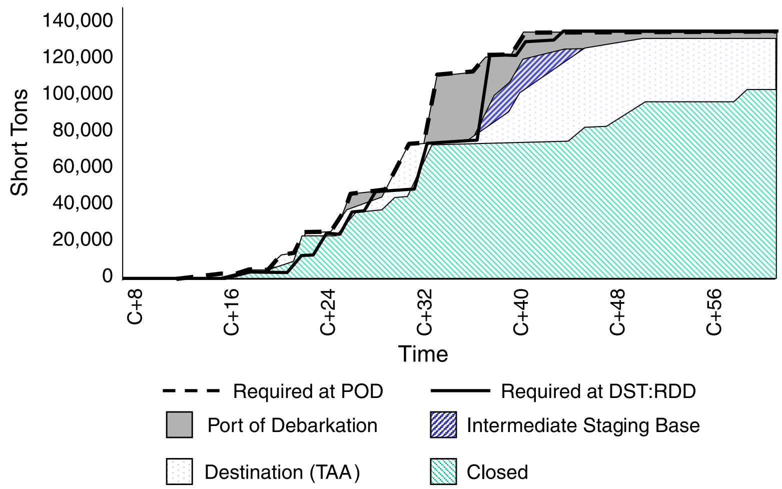

Figure 9. Delivery profile.

All Constrained Assets and Resources

Current Time: 50 11:13

Network: Caspian

Scenario: ARWG02-6May02

Resource	First Queued (Time)	Last Queued (Time)	First Used (Time)	Last Used (Time)	Max Interval Use (%)	#Intervals Used > 90% Capacity	Average Interval Use (%)
Intraheater Air Asset C-130 PAX only	−7 18:00	49 0:00	−4 0:00	49 11:39	100.0	213	97.88
Intraheater Air Asset ATT	−7 18:00	49 0:00	0 0:00	50 10:36	100.0	196	98.25
Azerbaijan Road Link 17 (Road Forward)			4 12:00	14 0:00	100.0	151	81.23
Geo Road Link 1 (Road Reverse)			−8 6:00	47 6:00	100.0	151	72.30
SWA Region Road Link—978 (Road Reverse)			4 18:00	14 0:00	100.00	151	81.30

Figure 10. Constraints report.

which the first event was put in a queue for the resource (or asset) is listed, as well as some other times of interest.

Note that the three road links in the table that are constrained do not have values for first and last queued times. This is because queues are associated with routes, rather than individual links, which do not have their own queues.

The analyst can use the information in the reports to examine each asset and resource more closely, and to consider options for alleviating the bottlenecks.

Higher-level reports give an overview of what is happening in the simulation. The table shown in Figure 11, for example, gives information about the numbers of ships arriving, off-loading, on-loading, and departing at every seaport berth group.

Low-level reports provide complete information about every activity performed by each bit of cargo and details about each convoy and train. Any unit components that could not meet their requirements for some reason are displayed in the error queue report along with the requirement and activity that led to the error.

All Constrained Assets and Resources

Current Time: 50 11:13

Network: Caspian

Scenario: ARWG02-6May02

Seaport	Berth Group	Arrivals	Departures	Intra Onloads	Intra Offloads	Strat Offloads
BATUMI-AZCY-PRT	BG Batumoi RoRo Berth	13	13	0	0	13
MERSIN-QBAL-PRT	BG Mersin Berth 1	6	6	0	0	6
MERSIN-QBAL-PRT	BG Mersin RoRo Container Berth 1	5	5	0	0	5
NOVOROSSIYSK-SDPM-PRT	BG Novorossiysk-Berth No. 39	5	5	0	0	5
NOVOROSSIYSK-SDPM-PRT	BG Novorossiysk-Berth No. 5	4	4	0	0	4

Figure 11. Overview report.

5. IMPLEMENTATION AND USE

The military logistics community has successfully used the previous version of ELIST (Version 7) in planning and training exercises for a number of years [11]. In the past few years, we have rewritten the original ELIST system to address the military's requests for more detail and more capabilities. The latest version of ELIST is written in the Java language with data stored in an Oracle relational database. To develop this new version, the application was structured into modular layers using object-oriented techniques. The resulting system is more reliable and easier to maintain; it also provides greater modeling flexibility.

ELIST is being used continually for many different types of analyses. A representative set of these analyses includes the following.

- ELIST is routinely used at U.S. Transportation Command TPFDD refinement conferences. Each theater of operation in the world is required to have plans ready to implement for a variety of contingencies. ELIST is used to determine if the plan is transportation feasible based on the commanders' RSO&I concept. Critical units are identified as arriving early at their tactical assembly areas, on time, or late, and to what degree. Lateness can be caused by a lack of assets, constraining infrastructure, a lack of essential personnel, or if the plan itself is too aggressive. ELIST is used to help identify and quantify these constraints. Looking at under-utilized infrastructure like seaports or airports, for instance, the analyst is able to make suggestions to the planners about shifting the late units to other ports.
- ELIST was recently used to support the Joint Staff's advanced mobility concepts study, which is a capabilities-based effort to examine military deployment using strategic and theater future concept transport vehicles. Unit closure times were compared using "high speed shallow draft sealift", "monohull sealift", "theater support vessel", "global reach transport aircraft", "ultra large airlifter", "heavy lift vertical takeoff and landing", and "super short takeoff and landing" concept vehicles. The study measured unit closure times at the tactical assembly areas and utilization of the theater transport vehicles when changing the weights, dimensions, and quantities of the vehicles. The study provided insights into which configurations and combinations of strategic and theater vehicles were the most effective in terms of being utilized and improving closure.
- ELIST has been used in various U.S. Army transformation studies. To support the U.S. Army interim division design analysis, ELIST in conjunction with the joint flow and

analysis system for transportation (JFAST) model evaluated the deployability of different designs for the Army's interim division by comparing legacy heavy and light divisions to the new designs. The study measured strategic responsiveness of the various division designs given three different theaters of operation. ELIST was used to determine how fast units could close at the tactical assembly areas and to identify theater choke points. The airlift and sealift arrival manifests from JFAST were passed electronically to ELIST which then offloaded the ships and aircraft, staged and moved the equipment and soldiers forward to their tactical assembly areas. ELIST was used to assess the interim division's organic composition in regards to self-deployability and reliability on host nation support assets. The study team was awarded the "Department of the Army Dr. Wilbur B. Payne Memorial Award for Excellence in Analysis Group Category 2002" for this study.

6. CONCLUSIONS AND FUTURE DIRECTION

ELIST provides tools for evaluating the transportation portion of military movement planning. Continuous interaction and feedback between the developers and the military logistics experts have led to a system that is viewed as useful and accurate by the users. Several additional initiatives are being considered for inclusion in ELIST.

ELIST has been integrated into the analysis of mobility platform (AMP) system [12]. Within this system, ELIST and the model for inter-theater deployment by air and sea (MIDAS) [5] have historically run serially. New work has begun on a dynamic capability, allowing the strategic arrivals to influence the theater deployment, and the theater deployment to affect the strategic deployment.

We would like to enhance the options for viewing and distributing results by expanding our simulation playback capabilities, by automatically generating presentation graphics, and by publishing the results to web pages.

To broaden the scope of the model, we would like to provide dynamic generation of sustainment throughout the theater. Using a manual process, current tools were used to provide some sustainment requirements for the MRS05 study. Automated tools would greatly simplify this task. In addition, more detailed modeling of the supply and consumption of fuels by all transportation vehicles would improve the accuracy of the results. Furthermore, results would be enhanced by having access to dynamic data from the actual executions. If ELIST had feeds of the current deployment status, planners could identify future problems and address them before they become critical.

Finally, many of the concepts and analysis techniques used in ELIST are applicable beyond the military. These techniques can be applied to other transportation sectors. For example, for the private sector, ELIST could be extended to analyze specialized freight shipments or perform analysis of fleet apportionment and distribution plans. Both private and governmental sectors could extend ELIST to analyze emergency and disaster scenarios, evaluating their effects as well as their contingency plans.

7. MILITARY FIELD MANUALS

(1) FM 5-101 Mobility
(2) FM 10-18 Petroleum Terminal and Pipeline Operations
(3) FM 10-67 Petroleum Supply in Theater of Operations
(4) FM 10-27 General Supply in a Theater of Operations
(5) FM 55-10 Movement Control
(6) FM 55-20 Rail Transport in a Theater of Operations
(7) FM 55-50 Army Water Transport Operations
(8) FM 55-60 Army Terminal Operations, FM 100-5 Operations
(9) FM 100-10 Combat Service Support

(10) FM 100-17 Mobilization, Deployment, Redeployment, Demobilization
(11) FM 100-17-1 Army Pre-Positioned Afloat Operations
(12) FM 100-17-2 Army Pre-Positioned Land
(13) FM 100-17-3 Reception, Staging, On-Ward Movement, & Integration (RSO&I)
(14) FM 100-17-5 Redeployment

REFERENCES

1. D.J. Reimer, Training and doctrine digital library, `http://www.adtdl.army.mil`.
2. *Deployment Planning Guide, Transportation Assets Required for Deployment*, MTMCTEA Reference 97-700-5, (July 1997).
3. *Logistics Handbook for Strategic Mobility Planning*, MTMCTEA Reference 97-700-2, (August 1997).
4. *Air Mobility Planning Factors*, AFPAM 10-1403, (June 1997).
5. C.J. Keyfauver *et al.*, *MIDAS Version 3.1 Users Manual (Draft)*, Vienna, VA, (May 2001).
6. C.N. Van Groningen, M.D. Braun, M.A. Clemmons, G. Lurie, K.L. Simunich, D. Timmerman, H. Vander Zee and M.A. Widing, *ELIST 8.1 User's Manual*, ANL/DIS/TM-62, Argonne National Laboratory, Argonne, IL, (February 2002).
7. M.D. Braun and C.N. Van Groningen, *ELIST 8 Transportation Model*, ANL/DIS/02-1, Argonne National Laboratory, Argonne, IL, (February 2002).
8. C.N. Van Groningen, M.D. Braun, M.A. Clemmons, G. Lurie, K.L. Simunich, D. Timmerman, H. Vander Zee and M.A. Widing, *ETEdit 8.1 User's Manual*, ANL/DIS/TM-63, Argonne National Laboratory, Argonne, IL, (February 2002).
9. *Joint Operation Planning and Execution System Volume II (Planning Formats and Guidance)*, CJCSM 3122.03, (June 1996).
10. M. Braun, G. Lurie, K. Simunich, C. Van Groningen, H. Vander Zee and M. Widing, ELIST8: A simulation system for transportation logistics planning support, In *Proc. 2000 Summer Computer Simulation Conference*, Vancouver, BC, July 16–20, 2000.
11. C. Macal, C. Van Groningen and M. Braun, Simulation of transportation movements over constrained infrastructure networks, In *Proc. 1995 Simulation Multi-Conference, Volume 4*, Phoenix, AZ, pp. 97–102, April 1995.
12. J.P. Tustin *et al.*, Integrating MIDAS and ELIST into the AMP HLA federation, In *Fall 2001 SISO Simulation Interoperability Workshop*, 01F-SIW-057, (September 2001).